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Change of Static and Dynamic Elastic Properties due to CO₂ Injection in North Sea Chalk

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SUMMARY

Reservoir modeling and monitoring uses dynamic data for predicting and determining static changes. Dynamic data are achieved from the propagation velocity of elastic waves in rock while static data are obtained from the mechanical deformation. Reservoir simulation and monitoring are particularly important in enhanced oil recovery by CO₂ injection (CO₂-EOR) in chalk as, chalk reservoirs are vulnerable to compaction under changed stress and pore fluid. From South Arne field, North Sea, we used Ekofisk Formation chalk having approximately 20% non-carbonate and Tor Formation chalk having less than 5% non-carbonate. We studied difference in static and dynamic behavior. Furthermore, brine saturated data were compared with CO₂ injected data to reveal the effect of supercritical CO₂ injection in both static and dynamic elastic properties. We used strain gauges and LVDTs to measure static deformation. We observed lower dynamic elastic modulus for chalk with higher non-carbonate content at porosities lower than 30%. In 30% porosity chalk, dynamic compressional and bulk modulus were found significantly higher than the static modulus. Static measurements with LVDT were found lowest. The effect of CO₂ injection was notable in dynamic elastic properties, while a possible change in static elastic properties was below detection limit.

Introduction

Enhanced oil recovery by CO₂ injection (CO₂-EOR) could be a potential method for getting extra oil from the depleted North Sea hydrocarbon reservoirs in chalk (Olsen, 2011). At the same time, alteration in the pore fluids due to CO₂ injection may cause change in stiffness and make a reservoir more susceptible to compaction (Plummer and Busenberg, 1982; Wolcott et al., 1989; Wellman et al., 2003; Hawkes et al., 2005; Madland et al., 2006; Xu et al., 2007; Zuta and Fjelde, 2008). Compaction is already a major challenge during production in the North Sea chalk fields (Hermansson and Gudmundsson, 1990; Kristiansen, 1998; Barkved and Kristiansen, 2005). This is particularly important during and after CO₂-EOR as there are huge concerns on stability of reservoir during production and leakage of CO₂ during and after production. Prediction of compaction in advance will help deciding production strategy. As dynamic methods are used for monitoring of static compaction, relationship between dynamic and static reservoir properties are required for reservoir simulation.

Reservoir compaction is generally monitored by 4D seismic utilizing changes in sonic velocity and changing thickness of reservoir layers. Changing thickness in reservoirs (static) is due to both elastic and plastic deformations. In contrast, sound wave propagation (dynamic) characterizes purely elastic behaviour. Numerous studies show significant difference between static and dynamic elastic properties (e.g. Simmons and Brace, 1965; Jizba and Nur, 1990; Tutuncu et al., 1994; Fjær, 2009). One reason is that the strain amplitude in sonic velocity measurement is very low compared to the strain amplitude of rock-mechanics tests (Simmons and Brace, 1965; Cheng and Johnston, 1981; Plona and Cook, 1995). Olsen et al. (2008) suggested that the difference in drainage condition between a static and a dynamic experiment is a major source of difference between measured static and dynamic properties. These observations suggest that there is a need for calibration of dynamic data with laboratory determined static data.

We studied the difference in static and dynamic elastic properties of chalk from South Arne field in the North Sea. We determined static compressional modulus and bulk modulus from rock-mechanical testing. On identical samples we estimated velocity of elastic waves and calculated the dynamic compressional and bulk modulus. We compared static modulus with dynamic modulus. We further studied the effect of supercritical CO₂ injection on both static and dynamic modulus of chalk.

Data

We used core material from the reservoir zone of South Arne field. For static test, we used 37.5 mm cylindrical plugs of 75 mm long, while for dynamic testing sample length was variable. Our study includes pure Tor Formation (CaCO₃>97%) and impure Ekofisk Formation (CaCO₃<85%). Due to the difference in mineralogy, rock-mechanical properties are different in these formations (Alam et al., 2011). Therefore, static and dynamic properties are also expected to be different.

We collected static data on five brine saturated (reference) and five CO₂ injected samples from each formation. Dynamic data was collected on 14 samples. The same samples were used at brine saturated condition and after CO₂ injection. Detail experimental procedure of this study is described by Alam et al., 2011. Olsen (2011) published fluid production data after CO₂ injection.

Theory and Method

Elastic Moduli of material defines how easy (or difficult) a volume can be changed when changing the effective stress working upon it. Compressional modulus determines the amount a material will deform in the direction of an applied (axial) stress. Bulk modulus indicates stiffness in both axial and radial direction and therefore determined from the volumetric strain. Compressional modulus is the most relevant parameter for a compaction study as it could be correlated with change in reservoir thickness by 4D seismic. In the following sections we described how static and dynamic compressional and bulk modulus was determined for this study.

Static properties:

The bulk modulus (K) was calculated based on expelled fluid (volumetric strain) and mean effective stress, calculated from stresses in axial (σ'_a) and radial direction (σ'_r) applied during uniaxial loading:

$$p' = \frac{1}{3}(\sigma'_a + 2\sigma'_r) \quad (1)$$

On the p' -volumetric strain curve, K is determined as the tangent at half the mean effective stress at yield. The modulus of uniaxial compaction was calculated from Linear variable differential transformer (LVDT) (M^*) and strain gauge (M) measurements produced from uniaxial loading. On the σ'_a -vertical strain curve M^* and M were determined as the tangent at half the yield stress.

Dynamic properties:

Compressional wave velocity V_p and shear wave velocity V_s were measured by recording the travel time of a transmitted ultrasonic wave at 200 KHz through a sample of known length. Measurements were performed under uniaxial stress condition by placing the sample between the two pistons of a loading frame and inside a triaxial cell at 4 MPa axial stress and 1 MPa radial stress (uniaxial stress condition). Dynamic elastic properties were calculated from the velocity of elastic waves and bulk density (ρ_b):

$$M = \rho_b V_p^2 \quad (2)$$

$$K = \rho_b V_p^2 + \frac{4}{3} \rho_b V_s^2 \quad (3)$$

Result and Discussion

Both bulk modulus and compressional modulus are correlated to porosity for both static and dynamic case. These parameters show notable difference according to the presence of non carbonate content at lower porosity. Ekofisk Formation with more than 15% quartz and clay shows lower stiffness than pure Tor Formation chalk below 30% porosity. Above 30% porosity the difference due to non carbonate content become insignificant. Therefore we compared static and dynamic data at this porosity.

For a 30% porosity brine saturated chalk, dynamic bulk modulus is 13 GPa to 16 GPa while the static bulk modulus measured by strain gauge is 3 GPa to 8 GPa (Figure 1a). LVDTs cannot be used for bulk modulus measurement as it measures deformation in one direction only. Compressional modulus measured for same porosity chalk from sound velocity, strain gauge and LVDT are 20 GPa to 25 GPa, 13 GPa to 18 GPa and 5 GPa to 10 GPa respectively (Figure 1c).

After CO₂ injection both bulk modulus and compressional modulus were found smaller than the brine saturated chalk (Figure 1b, d). It indicates that CO₂ injection could have a negative effect on the elastic stiffness properties of rock. One interesting observation is that the difference between dynamic and static values measured by strain gauges becomes smaller after CO₂ injection. At this condition the tested chalk samples contained 5% to 10% oil with rest filled with brine. There is possibility the changed fluid saturation effects sound velocity and consequently the dynamic elastic modulus.

Static data were found to be significantly lower than the dynamic data. Although strain gauge measurements are close to the dynamic compressional modulus, LVDT measurements indicates that the samples are less stiff. The strain gauge measures deformation over an interval of 1 cm of the sample and is less affected by the apparatus setup, but may not be representative for the whole sample if it is inhomogeneous. On the other hand, while LVDT measures over the entire length of the sample it may be affected by instrument setup, bedding and skew in the sample (Olsen et al., 2008). Therefore, investigation is required to find out the reasons for this discrepancy, relevancy of using static or dynamic data and the relationship between static and dynamic values.

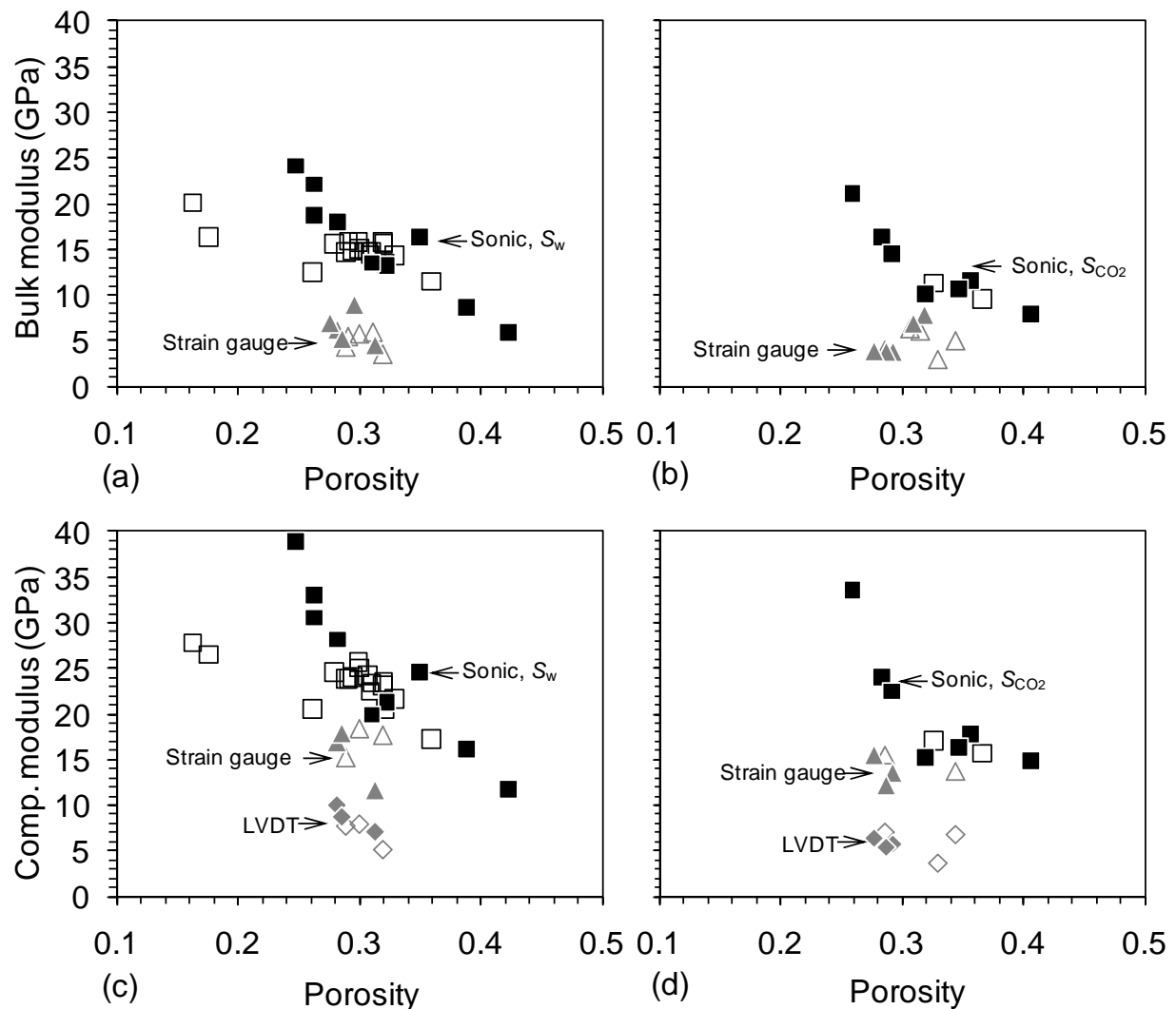


Figure 1 Modulus of the studied chalk: (a) Bulk modulus before CO_2 injection (reference samples for static data), (b) bulk modulus after CO_2 injection (CO_2 injected samples for static data), (c) Compressional modulus before CO_2 injection (reference samples for static data) and (d) Compressional modulus after CO_2 injection (CO_2 injected samples for static data). Black markers indicate dynamic data calculated from sonic velocity and bulk density and grey markers indicate static data measured by strain gauge or LVDT. Filled data points are Tor Formation samples and unfilled data points are Ekofisk Formation samples. Marker shape (square, circle, triangle and diamond) used for each procedure and experimental step is indicated by arrows.

Conclusions

Dynamic data demonstrate higher stiffness of reservoir rocks. Rock-mechanical models based on only dynamic data could underestimate any future reservoir compaction and subsidence. Relationship between dynamic and static data also depends on the type of chalk. Therefore it is necessary to establish relationships between static and dynamic data for each reservoir intervals.

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